AD-A131 396 WIND TUNNEL WALL INTERFERENCE(U) PRINCETON UNIV NJ DEPT OF MECHANICAL AND AEROSPACE ENGINEERING D B BLISS APR 83 AFOSR-TR-83-0655 AFOSR-77-3337 1/1

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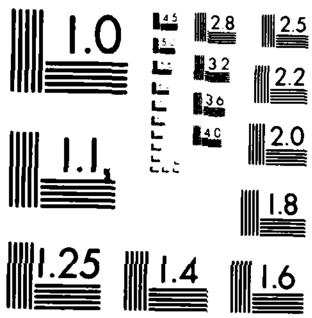

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FINAL REPORT TO THE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

on

WIND TUNNEL WALL INTERFERENCE

Grant AFOSR-77-3337
From 1 April 1977 to 31 March 1982

Submitted by

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April 1983

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 83-0655	2. GOVT ACCESSION NO. AD-A131 396	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) WIND TUNNEL WALL INTERFERENCE		5. TYPE OF REPORT & PERIOD COVERED FINAL 1 April 77 - 31 March 82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. B. Bliss		8. CONTRACT OR GRANT NUMBER(s) AFOSR 77-3337
9. PERFORMING ORGANIZATION NAME AND ADDRESS Princeton University Mechanical & Aerospace Engineering Dept. Princeton, NJ 08544		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2307A1 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NA Bldg. 410 Bolling Air Force Base, DC 20332		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wind Tunnel Wall Interference
Slotted Walls
Porous Walls
Adaptive Wall Wind Tunnels
Compliant Walls
Slot Aerodynamics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research was conducted on a broad range of topics related to wind tunnel wall interference. The aerodynamic behavior of an isolated finite length slender slot in a wind tunnel wall was analyzed. Numerical and analytical solutions were obtained relating the pressure differential to the average flow rate through the slot as a function of slot geometry for subsonic and supersonic flow. These solutions apply to the cases of linear and quadratic behavior corresponding to small and large slot flow rates. The analysis was extended to include the effect of an imposed pressure gradient along

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S/N 0102-LF-014-6601

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the slot. The results obtained are applicable to low aspect ratio holes as well as slots, and thus provide insight into the behavior of both slotted and perforated walls. The pressure gradient effect on holes was found to introduce a pressure gradient term in the averaged wall boundary condition for perforated tunnel walls. The effect of aerodynamic interference between holes in a perforated wall was studied for two-dimensional and three-dimensional configurations using a wavy wall model problem. It was found that the interference effect between wall elements is relatively local over a wide range of parameters, thereby allowing it to be represented by an additional term in the averaged wall boundary condition. The interference effect takes the form of a streamline curvature term. The concept of a compliant wall wind tunnel was explored by the analysis of a model problem to demonstrate a particular flexible wall concept. In the area of adaptive wall wind tunnels, a method was developed which shows how control adjustments should be made to converge very rapidly to interference-free conditions.

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1.0 INTRODUCTION

This report summarizes the achievements of a five year program conducted at Princeton University under AFOSR sponsorship to study fundamental issues in the area of wind tunnel wall interference. The primary topics addressed by this research program were:

- the physics of flow through slots and holes in wind tunnel walls.
- the nature of the averaged wall boundary condition for perforated walls.
- a flexible wall wind tunnel configuration.
- a convergence method for the controls of adaptive wall wind tunnels.

Work on some of the topics listed above extends beyond the five year period due to an additional grant. The following sections provide an overview of the technical issues addressed and a summary of the technical results of the research program. A list of the resulting publications and the participating personnel is also provided.

2.0 REVIEW OF TECHNICAL ISSUES

Wind tunnel wall interference is an issue of renewed concern due to the need to use larger models to achieve high Reynolds number and due to the importance of obtaining accurate results at transonic speeds, where interference is most severe. There is an ongoing effort by researchers in this area to understand the causes of interference and to resolve the inconsistencies in results obtained in different facilities. It has long been recognized that ventilated (slotted or perforated) wind tunnel walls can significantly alleviate many interference problems and tunnels of this type are widely used. However, many aspects of the aerodynamic behavior of ventilated tunnel walls need improved understanding if very accurate interference corrections are to be made.

An increasingly common approach is to use a conventional ventilated wall tunnel and make supplementary flow measurements near the walls[1]. Interference corrections can then be made on the basis of the actual state of the flow near the wall. This approach is taken because our understanding of the fluid mechanics of slotted or perforated walls is imperfect. The difficulty with this method is that a large number of additional measurements is required and the complexity of the experiment is increased. At the very least, a better understanding of the wall behavior would reduce the number of required wall measurements and allow them to be used in a more accurate way.

A recent important development is the so-called intelligent wall wind tunnel concept[2]. The flow rate through ventilated walls is controlled as a function of location along the wall by external means. Flow quantities

are measured at stations near the wall and adjusted in an attempt to simulate free field conditions, and thereby eliminate, or at least minimize, wall interference. A promising alternative approach is to use deformable solid walls to reduce interference. As with conventional designs, the ventilated intelligent wall tunnel can still benefit from a better understanding of wall behavior. Furthermore, any form of intelligent wall concept requires a method to adjust wall parameters so that convergence free conditions are rapidly achieved.

To account for ventilated wall behavior, equivalent homogeneous boundary conditions have been proposed for various wall geometries. This approach seems reasonable provided that the density of slots or perforations is sufficiently high that it is meaningful to speak of an average behavior of the wall surface. The boundary conditions involve certain coefficients reflecting the average wall properties.

Generally, both slotted and perforated walls have been represented by a homogeneous boundary condition of the form,[3,4]

$$\phi_x + K_p\phi_z + K_s\phi_{xz} + K_Q\phi_z^2 = 0 \qquad (1)$$

where ϕ is the velocity potential, x is the streamwise coordinate, z is the coordinate normal to the wall, and K_p, K_s, K_Q are coefficients which depend (at least) on wall element geometry and Mach number. The first term on the left is associated with the perturbation pressure; the second term is an effective flow resistance due to normal flow; the third term is associated with streamline curvature; and the last term is a nonlinear pressure drop

associated with flow separation. Depending on the type of wall element, different terms in the boundary condition are important[4]. For instance, the flow resistance coefficient K_p is much larger for holes or perforations (aspect ratio ~ 0 [1]) than for slender slots (aspect ratio << 1); the streamline curvature term is important for slender slots, and the current research also shows a similar term for holes.

Considerable theoretical and experimental work has been done to determine the coefficients in Equation (1) for slender slots[3-10]. The theoretical work has typically involved the use of slender body theory. Analytical formulae have been proposed for the streamline curvature coefficient, K_s, and the nonlinear pressure drop term, K_Q, for a wall covered with a row of streamwise slots. An analytical expression for the linear flow resistance coefficient, K_p, when the slot is tapered has also been proposed. The present research has shown that finite length slots also exhibit linear behavior, even if untapered.

For perforated walls, the fluid mechanics of the flow through the individual holes can be very complex, particularly if the hole aspect ratio is of order unity and if the wall thickness is comparable to the hole diameter, which is often the case. Given the difficulty of analyzing a high speed impinging separated flow, the flow resistance coefficient, K_p, is usually determined experimentally[9]. The holes are sometimes shaped or angled to give a certain desired behavior. The problem is that the experimental determination implicitly assumes that for a given wall geometry, K_p depends only on a few overall flow parameters. In fact, the current work has demonstrated that the wall behavior also depends on the local applied

pressure gradient. The effect of gradients has been incorporated into the averaging procedure. A term involving ϕ_{xx} was found from studying the behavior of slots and holes subject to an applied pressure gradient[11]. There is also a term involving ϕ_{xz} even for perforated walls[12], even though the proportionality constant K_s does not have quite the same physical interpretation as for a slotted wall[10]. As the results illustrate, this effort involved a re-examination of the basic form of the boundary condition Equation (1). Some of the new effects identified are relatively small, however it is interesting to note that they are on the same order as the recently developed corrections to boundary layer thickness variation[13,14]. These are also associated with a gradient term in the averaged wall boundary condition.

Fundamentally, the wall boundary condition depends on the aerodynamics of the individual elements that make up the wall (slots or holes) and on the aerodynamic interference between these elements within the region over which the averaging takes place. Although wall boundary conditions have received considerable attention many basic issues remain unresolved. A major objective of the research program was to address a number of these issues as they pertain to ventilated walls. Both the aerodynamics of wall elements and the interference between wall elements were of concern. The advent of new approaches to the wind tunnel wall interference problem has increased, rather than diminished, the need to understand the basic physics of the flow near a ventilated wind tunnel wall.

3.0 RESEARCH ACTIVITIES

The major research areas and their most significant results are described in the following sections.

3.1 Slender Slot Aerodynamics

The aerodynamic behavior of an isolated finite length slender slot in a infinite wall beneath a high speed potential flow was investigated[10,11]. This analysis was undertaken because it is important to understand the behavior of a basic wall element in isolation before considering a wall made up of many such elements. The analysis has contributed to the understanding of both slotted walls and perforated walls made up of low aspect ratios holes.

The theoretical model of the flow through a single finite length slot was constructed using slender body theory[10]. The original work considered only the case of a uniform stream above the slot, so there were no variations in the moving stream static pressures except those induced by the slot flow itself. The inner solution was found to be a two-dimensional crossflow in the vicinity of the slot governed by Laplace's equation. The outer solution is a line sink in the compressible flow field. Two limiting cases were considered in detail: small free surface deflection corresponding to a small pressure differential across the slot; and large free surface deflection (fully developed crossflow) due to a large pressure differential. In the first case the pressure drop is linearly related to the flow rate, and in the second case it depends on the square of flow rate.

The general analysis showed that the magnitude of the crossflow at any point is significantly affected by the crossflow at other points along the

slot. This effect is caused by the outer solution which involves the sink strength distribution in the streamwise direction. The problem formulation leads to an integral equation as a consequence of this interaction. This equation was solved numerically for small free surface displacements. However, a significant result was the discovery of analytical solutions for certain fairly realistic slot planforms. A simple analytical solution was also possible for the case of large free surface displacements, since the coupling between points along the slot is then higher order. A comparison of calculated results with available experimental data suggest good qualitative agreement in both the linear and quadratic regimes, with both theory and experiment exhibiting only weak Mach number dependence.

The work on isolated slot aerodynamics was extended to include the effect of pressure variations along the slot length[11]. These variations would arise as the result of a nonuniform disturbance flow field, such as caused by a model within a wind tunnel. A modified integral equation results which has roughly the same form as that for the constant pressure differential case. The equation can be solved by similar numerical procedures. However, for the same special slot planforms mentioned earlier, analytical solutions can be obtained if the imposed pressured variation along the slot is expressible as a polynomial. Specific results were obtained for the case of linear pressure variation (constant pressure gradient). These results give physical insight into the effect of pressure gradient on the flow rate through slots and low aspect ratio holes. There is an analogy between flow through a hole and flow over a lifting wing. In fact,the effect of an imposed pressure gradient

along a hole or slot is somewhat similar to the effect of camber on a lifting surface.

An important consequence of the above results is that if an averaged boundary condition is desired for a tunnel wall perforated with low aspect ratio holes, there should be a term involving the effect of local pressure gradient on hole behavior. Reference 11 shows that a term of the form $K_g\phi_{xx}$ should be added to the left hand side of Eq. (1). The constant K_g depends on hole geometry and Mach number. As discussed in the next section, research on the averaged boundary condition shows that there is also a term associated with the aerodynamic interference effect between holes.

3.2 Averaging Methods for Perforated Walls

A perforated wall having sufficiently high hole density can be approximated by an equivalent averaged wall boundary condition. The goal of this phase of the research program was to find the form of the averaged wall boundary condition which most accurately reproduces the perforated wall behavior. An important feature of the analytical approach to this problem was that the behavior of an isolated hole was assumed to be known. This behavior is the fundamental building block used to construct the characteristics of the perforated wall. Because of this approach, the contributions of the basic hole and the interference between holes are identified and separated. The inclusion into the averaged boundary condition of the mutual interference effect between holes was of primary interest.

The problem was first approached[12] by means of a wavy wall problem. High speed flow was assumed to pass through a channel bounded above by a rigid,

impervious wavy wall (simulating a model) and below by a flat wall (simulating a wind tunnel wall). Inviscid, irrotational, compressible flow was assumed, and the effect of streamwise and spanwise wavy perturbations of the upper wall were considered. The lower wall was modelled as being either two-dimensional (transverse slotted) or three-dimensional (perforated), or as a continually porous wall having the properties of an averaged boundary condition. The approach was to find the properties of the continually porous wall which most nearly duplicated the upper wall pressure distribution produced by a perforated lower wall.

The advantages of studying the wavy wall problem are that it is relatively simple analytically, all the potentially important physical effects are present, and the important parameters are easily identified and controlled, e.g., the pressure gradient is determined by the wall wavelength. The wavy wall simulates the wind tunnel model in a particularly convenient manner since the problem geometry is simple and the disturbance flow field can be characterized by a minimum number of parameters. With this configuration, the detailed effect of discrete perforations on the pressure distribution on the wavy wall can be calculated. Since relatively few geometric parameters (channel height, slot spacing, and wall wavelength) are needed to define the configuration, and since these can be varied independently, the important functional dependences can be easily identified.

The perforated lower wall was modelled as a distrbution of point sources and sinks placed along an otherwise rigid boundary. The flow field in the channel can then be thought of as an outer solution, and the local fluid

mechanics in the vicinity of each hole (assumed known independently) can be thought of as an inner solution. The channel flow with a perforated lower wall, was solved using an image system.

It was found that the for realistic hole densities and wall separations, the lower wall could indeed be represented by an equivalent continuous porous wall. This is because the effect of discrete holes smooths out rapidly with increasing height above the perforated wall. However, to obtain good agreement it was necessary that the effective porosity of the equivalent porous wall be complex. Essentially, the perforated wall response is slightly phase shifted due to the aerodynamic interference between the holes. It was also found that this interference effect was relatively local in realistic cases, i.e., the effect of images and distant holes could be neglected. This local behavior allows the results of the wavy wall problem to be generalized since the perforated wall effect can then be represented by a local boundary condition. A detailed justification is given in Reference 12.

The form of the averaged boundary condition for a perforated wall in the linear flow regime is found to be,

$$\phi_x + K_p\phi_z + K_i\phi_{yz} + K_g\phi_{xx} = 0 \qquad (2)$$

The flow resistance coefficient K_p turns out to be the flow resistance coefficient for an isolated hole converted to an equivalent porosity. The constant K_i is associated with the interference between holes and depends on the spanwise and streamwise hole spacing and the Mach number. Its exact

theoretical form is discussed in Reference 12. Note that the interference effect for a perforated wall is similar to the streamline curvature term in the slotted wall boundary condition. The constant K_g is associated with the pressure gradient effect on an isolated hole, described in Section 3.1 and in Reference 11.

The last two terms in Eq. (2) represent effects present in the behavior of perforated walls that have apparently gone unrecognized. In practice these effects turn out to be relatively small, although they show a trend of increasing importance with increasing Mach number. However, they are of comparable order to other effects currently being accounted for in sophisticated wall correction procedures. As part of the research effort, sample calculations were performed to demonstrate the effect of these terms on the lifting and thickness problems for two-dimensional airfoils in a perforated wall channel.

3.3 Compliant Wall Wind Tunnel

A flexible wall wind tunnel has impermeable flexible walls which are deformed by the application of external forces to minimize wall interference. This concept is an alternative to the ventilated "intelligent" wall tunnel. Actually, both are closely related by the fact that the conditions at the tunnel boundaries are actively adjusted according to some criterion to minimize interference. The concept of a compliant wall wind tunnel which would be self-correcting goes a step further. The idea is to construct the walls in such a way that the aerodynamic loads would cause the walls to deform naturally to minimize interference. A preliminary study of some aspects of this concept was conducted as a part of the research effort.

The effect of a simple flexible tunnel wall on the interference on a flat plate airfoil in supersonic flow was studied[15,16]. The flexible wall was modelled as an appropriately positioned hinged plate with a torsional spring at the hinge line. It was shown that the system parameters could be chosen so that the flat plate wall element deflected to prevent wave reflection from the wall. Front and rear hinge locations were considered and the front location was judged to be best. It was shown that the analysis could be generalized to multiple-segment walls. This generalization would allow for a much wider range of flow regimes and wall characteristics but at the cost of increased complexity analytically and experimentally. Nevertheless, the study indicated that the compliant wall concept is promising and deserves attention in the future.

3.4 Control Laws for Adaptive Wall Wind Tunnels

In an adaptive wall wind tunnel the flow conditions are modified by adjusting conditions at the tunnel walls to minimize interference. In existing designs, this modification is achieved either by deforming flexible impervious walls, or by actively adding or removing flow through ventilated walls. In either case, it is necessary to adjust the wall to interference free conditions in an efficient manner starting from some initial state. This problem was addressed in connection with the present research effort and an effective procedure was developed[17].

Typically a set of flow variables is measured at discrete points near the walls. A certain known theoretical relationship between these variables

exists for interference free conditions, e.g., the same relationship that would apply if an exterior flow field replaced the tunnel walls. This relationship must be achieved by adjusting the adaptive wall controls. The new procedure is to first determine influence matrices relating the wall control changes to the measured wall quantities. The matrices contain the effect of each wall control change taken individually on every measurement point. In practice, these matrices must be obtained experimentally. Given these matrices it is possible to develop a simple formula for the set of control adjustments that eliminate interference. If the behavior of the system is entirely linear, the interference free state can be achived by a single set of adjustments. If the system contains nonlinearities, it is still possible to use the procedure to step to the answer in quasi-linear increments. In this case the influence matrices must be determined repeatedly. It is also possible to implement the scheme in a least squares sense when the number of measurements exceeds the number of controls. In general, this scheme appears to be superior to the iterative schemes used previously.

4.0 PUBLICATIONS AND PROFESSIONAL PERSONNEL

4.1 Publications

The following publications were prepared:

"Aerodynamic Behavior of a Slender Slot in a Wind Tunnel Wall," AIAA Journal, Vol. 20, No. 9, September 1982, pp. 1244-1252, D. B. Bliss.

"Pressure Gradient Effect on a Slender Slot in a Wind Tunnel Wall," (accepted for publication in the AIAA Journal), D. B. Bliss.

"A Study of the Averaged Boundary Condition for Perforated Wall Wind Tunnels Including the Effect of Gradients" (to be submitted to the AIAA Journal), D. B. Bliss, and P.-J. Lu.

"A Compliant Wall Supersonic Wind Tunnel," AIAA Paper No. 79-0110, presented at the 17th Aerospace Sciences Meeting, New Orleans, LA, January 1979, E. H. Dowell.

"A Compliant Wall Supersonic Wind Tunnel," Aeronautical Journal, October 1978, E. H. Dowell.

"Control Laws for Adaptive Wall Wind Tunnels," AIAA Journal, Vol. 19, No. 11, pp. 1486-1488, 1981, E. H. Dowell.

4.2 Professional Personnel

The professional personnel associated with the research effort were Professor D. B. Bliss, Professor E. H. Dowell, P.-J. Lu (graduate research assistant), and T. R. Quackenbush (undergraduate research assistant).

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11. Bliss, D. B., "Pressure Gradient Effect on a Slender Slot in a Wind Tunnel Wall," (accepted for publication in the AIAA Journal).

12. Bliss, D. B. and Lu, P.-J., "A Study of the Averaged Boundary Condition for Perforated Wall Wind Tunnels, Including the Effect of Gradients," (to be submitted to the AIAA Journal).

13. Adcock, J. B. and Barnwell, R. W., "Effect of Boundary Layers on Solid Walls in Three-Dimensional Subsonic Wind Tunnels," AIAA Paper-83-0144, presented at the AIAA 21st Aerospace Sciences Meeting, Reno, NV, January 10-13, 1983.

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